STRENGTH OF COMBINED MATERIALS (SURVEY)

G. N. Mekhed

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16. Abstract

Review of studies dealing with the strength character-istics of a class of materials which are composed of two or more macro- or microcomponents different in shape and compo-sition, insoluble in each other but firmly bonded with each other in the combined material. The materials include lami-nar compositions, compositions consisting of particles with or without binders, fiber composites with or without binders, flake-filled composites with binders, and composites with a skeleton and a filler consisting of different materials. The strength of these materials is assessed and suggestions are given for improving their mechanical performance.

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A combined material should be understood to be an artificial /169* combination of two or more macro- or microcomponents, which differ from one another in shape and composition, are insoluble in each other, but are firmly bonded with each other.

Combined materials can be divided into three categories, by method of production: the first group concerns materials, produced by means of mixing two or more ingredients; the second are laminar and the third are reinforced materials [6].

One of the most well-known and cheapest materials, concrete, which is produced from a mixture of cement, sand, gravel and water, can serve as an example of the component materials of the first category.

In this case, the particles of one material are incorporated into a matrix of a another material.

Sometimes, reinforcing particles are grown from the matrix, as occurs in aging.

Combined materials can be formed in the following manner: 1) metal-metal; 2) metal-inorganic substance; 3) metal-organic substance; 4) metal-inorganic substance-organic substance; 5) inorganic substance-organic substance; 6) inorganic substance-inorganic substance; 7) organic substance-organic substance. Usually, in producing combined materials, materials are used, in the form of fibers, plates, flakes and whiskers of fillers and binders. In matrix type combined materials, the basic material is a binder.

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* Numbers in the margin indicate pagination in the foreign text.

The interfaces in combined materials are of great importance; they can be either a solid phase or a coating on one of the hardening elements.

The distribution of components is a no less important characteristic of combined materials; it can be random, regular or systematically repeating.

A recently introduced classification of combined materials includes five groups, according to the state of these materials:

1. Laminar combined materials, consisting of individual layers or laminar components;

2. Combined materials of particles, with or without a binder base;

3. Fibrous combined materials of fibers, with or without a binder base;

4. Flake combined materials of flat flakes with a binder base;

5. Combined materials with a filler or, as they also are called, skeleton combined materials, which consist of a basic skeleton material, with a filler of a different material.

It has long been known that two-phase combined materials have higher strength than single phase, homogeneous ones.

Cracks forming in a homogeneous material rapidly propagate through a section, which leads to destruction of the material.

A two-phase material usually consists of a material with high strength and high modulus of elasticity and a material with a relatively low modulus of elasticity.

In a combined material, the high-strength component most often prevails over the lower strength one uniformly distributed in it. Upon application of a force, the component with the low modulus of elasticity is deformed and destroyed, and the stresses are taken up by the high-strength component. At the same time, isolation of imperfections existing in the high-strength component

prevents propagation of cracks through the entire section of the sample. There are very many two-phase, high-strength materials in nature. Thus, wood is a combination of high-strength cellulose with weaker lignin. The longitudinal fibers of bamboo have a modulus of elasticity on the order of 2800 kgf/mm^2, while the remaining bulk has only 700 kgf/mm^2 in all, i.e., one quarter as much [1, 2].

Therefore, with any failure of one of the fibers, the load is transmitted to the next wood fiber. Mankind has used combined materials since ancient times: ancient wooden cannon with steel bands, wooden wheels with steel tires [3], etc. The celebrated India steel blades and blades from Toledo and Japan were of a two-phase composition.

What modern combined materials are, what their nature is and why the acute necessity for them arose can be seen from the following examples. Since space flight is introducing more and more rigid requirements for mechanical and thermal properties of materials, a distinct description is necessary of what materials can operate under conditions of intense thermal action (the heat of rocket engines, the heat of friction of the dense layers of the atmosphere in injecting space objects into orbit and in their return to earth) and the effect of high vacuum (10^{-6}-10^{-12} mm Hg), ozone from solar irradiation, dissociated and ionized gasses, cosmic rays, meteorite particles and weightlessness, and their properties, as well as the medium in which they have to operate must be studied. Certain expected conditions of reentry of space objects into dense layers of the atmosphere are represented in Fig. 1 [4].
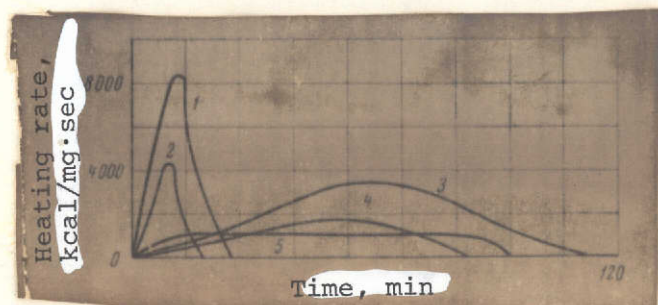

Fig. 1. Conditions of entry of spacecraft into dense layers of the atmosphere: 1--reentry of intercontinental ballistic missile; 2--reentry of intermediate range ballistic missile; 3--reentry from hyperbolic trajectory; 4--reentry from elliptical orbit; 5--reentry from ballistic trajectory.

Individual parts of rockets operate under very high temperature drops: thus, the liquid fuel tank must withstand a low temperature (-250°C) and the combustion chamber, a very high one (+3500°C). Upon reentry into the dense layers of the atmosphere, the rocket skin is heated to 5000-7000°C.

As a consequence of heating and evaporation, the maximum operating temperature for materials used at the present time should not exceed 4000°C. With high resistance to alternating tempera- /171 tures and mechanical stresses, material for rockets must have a low specific weight, good chemical stability, the highest possible strength at high temperatures and a high melting temperature [5].

The temperature range, in which metals and alloys (except refractories) can operate for a long time, is limited to 980°C. The temperature region above 1315° is of interest, during long flights at hypersonic velocities. Only a limited number of materials can operate in the temperature range above 980°, namely: 1) refractory materials with coatings; 2) cermets; 3) ceramics; 4) graphites; 5) fitting type materials for heat protection systems, which break down during operation; 6) the newest class of combined materials, metals strengthened with dispersed particles.

Analysis of the properties of existing materials indicate that standard individual materials are not capable of satisfying these very high requirements.

Creation of combinations of individually selected materials (compositions), for the purpose of satisfying the specific requirements of special fields of technology, may be a way out of the situation produced, in which the following must be maintained:

Maximum strength; compatibility and capability of operating in a specific environment; minimum cost.

The need of space technology for materials with maximum strength is becoming clear, from a comparison of the weight of materials used to fabricate flight vehicle accelerators, with the weight of the useful load injected into orbit.

Thus, the ratio of accelerator weight to weight of useful load reaches 100:1, and the ratio of the weight of the entire launch and accelerator system to the weight of the useful load is on the order of 1000:1.

Combined materials, intended for operation under conditions of high thermal flux rates, can be divided into three groups: ablative, structural, used mainly for bearing the loads of structural parts, and materials fulfilling both of these functions.

The creation of new combined materials is inescapably based on many empirical materials. However, full realization of the advantages of combined materials is possible, only when a scientific theory of these materials is created and the basic technology of their production is developed and applied.

The operating properties of structural materials can be appreciably increased, by means of reinforcing them. This is evident in Fig. 2 [7], in which the strength-weight (or specific strength) ratio is presented, for the period 1900-1980. The noticeable improvement in properties achieved in the past 50 years is evident from the curves for steel and aluminum. The strength of titanium and its alloys also has been noticeably increased in the past decade. However, fibrous combined materials will evidently be the basic potential structural, high-strength materials for a long time.
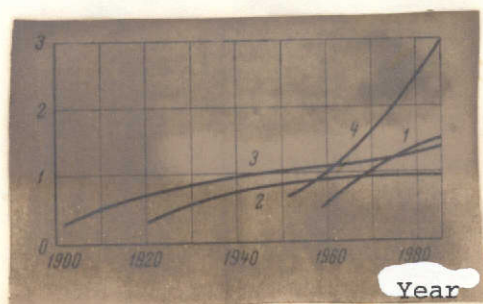

Fig. 2. Specific strength (strength:specific weight ratio) of various structural materials in the period from 1900 to 1980: 1--titanium; 2--aluminum; 3--steel; 4--composite materials.

In 1940, materials with a high strength-weight ratio, based on plastics and reinforced glass cloth were developed, and the

increase in specific strength has continued, right up to recent times.

Whiskers produced at present permit a still greater increase in the strength-specific weight ratio of high-temperature materials. The strength of whiskers has almost reached the theoretical strength of crystalline materials. A proposal was expressed in 1957, of the possibility of using whiskers for reinforcing various materials. Materials in fiber form are almost always stronger than solid ones /172 (in large cross sections). In general form, the finer the fiber, the greater the strength it has.
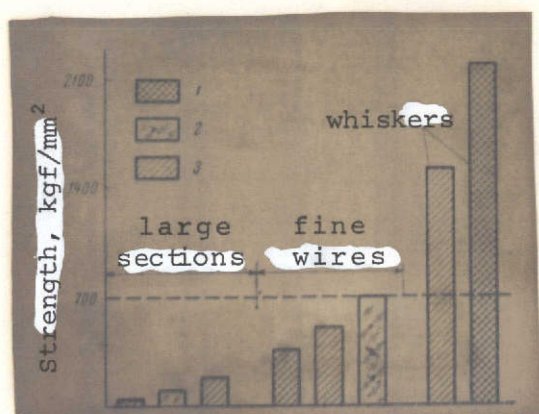

Fig. 3. Strength of metals, glasses and ceramics in large sections, wire and whiskers: 1--ceramics (Al_2O_3; Si1; Si_3N_4; BeO; C); 2--glass; 3--metals.

Thus, fine, monocrystalline whiskers, with perfect structures, have higher strength than the same material, of the same composition, but in a larger cross section. This is evident from Fig. 3, in which the strength of whiskers, fine wires and materials in large sections are compared. Wires and large sections of glasses and metals have great strength; however, ceramics in the form of whiskers have the highest strength.

A comparison of the strengths of various materials, in the form of fine filaments, with their rigidity (Young's modulus) is given in Fig. 4.

The straight line in Fig. 4 is the theoretical strength, equal to 10% of the modulus of elasticity. On this basis, certain types of fiberglass very closely approach their predicted theoretical strength, while metal polycrystalline and multiphase filaments are still far from reaching the theoretical strength. Although the

strength of whiskers still does not attain the theoretical strength, they nevertheless have the highest strength and modulus of elasticity.
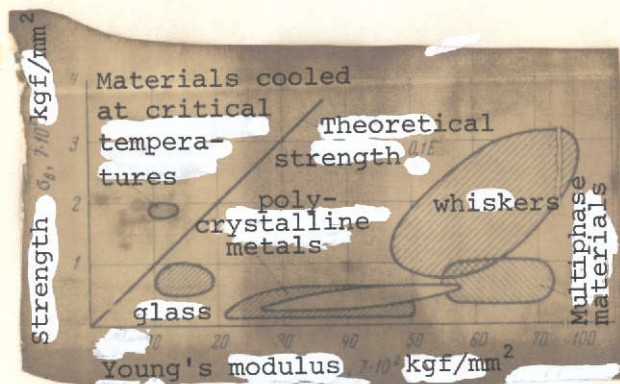

Fig. 4.   Strength and Young's modulus of various fiber materials.

Thus, from the mechanical point of view, they are of interest as a reinforcing material. The strength-specific weight and modulus of elasticity-specific weight ratios for whiskers are presented in Figs. 5 and 6. It is evident from the figures that graphite whiskers have the highest strength-specific weight and modulus of elasticity-specific weight ratios. Whiskers of BC are in second place. Then, whiskers of Al_2O_3, BeO, SiC and Si_3N_4 follow. Fiberglass SiO_2 has a better strength-specific weight ratio, but because of the low Young's modulus, the Young's modulus-specific weight ratio of fiberglass is very low. Finally, metallic whiskers of such metals as iron have low strength-specific weight and Young's /173 modulus-specific weight ratios, because of their high specific weight.

In use of these new fiber materials for reinforcing, others of their properties should be kept in mind. Thus, a graphite fiber loses its properties upon interacting (chemical reaction and diffusion into metals at high temperatures) with other materials. However, whiskers of other materials, for example, B_4C, Al_2O_3, SiC

and Si_3N_4, can be used successfully, combined with certain metals. The strength and elasticity of whiskers of certain materials are presented in the table. The
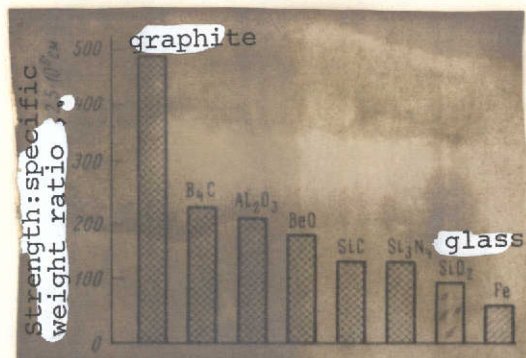

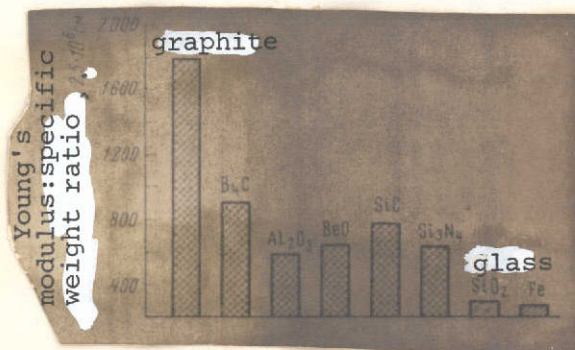Fig. 5. Strength:specific weight ratio for whiskers of certain materials.

Fig. 6. Young's modulus:specific weight ratio for whiskers of certain materials.

Mechanical Properties of Whiskers of Certain Materials

Материал усов	Предел прочности, кГ/мм²	Предел упругости, кГ/мм²	Литературный источник
SiC	2.1—7.0·10²	4.9·10⁴	[5, 8]
Al₂O₃	1.4—3.4·10²		[9, 13]
Graphite	2.1·10²	3.5·10⁴	[9]
Si₃N₁	7·10²		[10]
Glass, { E grade A-994	3.5·10² / 4.5·10²	7.4·10³ / 8.7·10³	[11] / [11]
ZrO₂	3.5·10²	3.5·10³	[11]
Spinel Li—Al	7·10²		[11]
Quartz	6·10²		[12]
Fe	1.4—1.4·10²		[14]

The basic criteria for reinforcing can be formulated in the following manner.

1. The strength and modulus of elasticity of a reinforced /174 material must be greater than these parameters for the matrix.

2. The bulk fraction of the whiskers must be sufficiently large to ensure strengthening of the matrix material.

3. There must be a good and elastic bond between the reinforcing phase and the matrix.

4. The coefficient of thermal expansion of a reinforcing material must coincide with the coefficient of thermal expansion of the matrix material, by which weakening and disruption of the bonds between the reinforcing material and the matrix, taking place with a difference in the coefficients of thermal expansion, is prevented.

5. The reinforcing material must be chemically compatible with the matrix, so as not to permit harmful chemical reactions at the reinforcing phase-matrix boundary.

6. The ends of the reinforcing phase filaments must have a conical or rounded shape, (for the purpose of decreasing concentration of stresses in the matrix). The areas of contact boundaries of the reinforcing phase and matrix must be at a minimum, for the purpose of preventing weakening or dissolving of the reinforcing phase filaments.

7. The reinforcing phase filaments must retain stability at room and elevated temperatures and, besides, a large part of their strength at elevated temperatures.

8. For the purpose of achieving the maximum strength, the reinforcing phase must be appropriately oriented and distributed in the matrix.

Many of the criteria listed are maintained in strengthening metals with whiskers, produced in the matrix itself, by means of controlled cooling of liquid melts of eutectic composition.

In strengthening metals with whiskers, by means of controlled cooling of liquid eutectic melts, the following are achieved:

a) Excellent spatial distribution and directionality of the reinforcing phase, owing to which the difficult problem of combining and dispersing the whiskers in the matrix is solved;

b) Formation of whiskers with conically shaped ends, which facilitates a decrease in stress concentration in the matrix surrounding the ends of the whiskers;

c) Excellent adhesion between the reinforcing phase and the matrix, which ensures good transmission of shear loads;

d) Chemical compatibility of the reinforcing phase and the /175 matrix.

There is no theoretical limitation, with respect to the weight of the ingot produced.

In selection of the production technology of reinforcing materials, it must be kept in mind that a reinforcing additive may be continuous and discrete, i.e., have great length.

In using unidirectional, continuous reinforcing additives, the mechanical behavior of the combined material can run through four stages [16] (it is contemplated here that the reinforcing additive is incorporated in a soft, viscous matrix, with a low modulus of elasticity E). In the first stage, the reinforcing additive and matrix are elastically deformed; in this case

$$E_c = E_r V_r + E_m V_m, \tag{1}$$

where the subscripts mean: c -- combined material; r -- reinforcing additive; m -- matrix; E -- Young's modulus; V -- bulk fraction of each component.

In the second stage, the reinforcing filaments continue to deform elastically but, here, the matrix deforms plastically.

In this case

$$E_c = E_r V_r + (d\sigma_m / de_m) V_m, \tag{2}$$

where $d\sigma_m/d\varepsilon_m$ is the slope of the stress-deformation curve for the matrix, with a deformation of the combined material of ε_c. Thus, for many materials

$$d\sigma_m/d\varepsilon_m \cdot \varepsilon_m \cdot 100,$$

and expression (2) can be reduced to the form

$$E_c = E_r V_r.$$

In the third stage, both the reinforcing additive and the matrix are subject to plastic deformation. In this case, the reinforcing additive is not destroyed. The fourth stage is characterized by destruction of the reinforcing component; sudden failure of the combined material takes place in this case.

Assuming that $V_r > V_{cr}$, the strength of the combined material can be determined from the expression

$$\sigma_c = \sigma_r^1 V_r + \sigma_m (1 - V_r), \tag{3}$$

where σ_r is the strength of the reinforcing additive filament, σ_m is the stress on the matrix, corresponding to the strength of the reinforcing filaments.

Equations (1) - (3) were verified experimentally, for combined materials of the tungsten-copper, stainless steel-aluminum and other types.

For the values $V_r < V_{cr}$, adding reinforcing filaments does not lead to strengthening (Fig. 7); since $V_r = V_{cr}$,

$$\lim \sigma_r V_r + \sigma_m (1 - V_{cr}) = \sigma_u,$$

where $\sigma_u = \sigma_b$ of the matrix, from which $V_{cr} = (\sigma_u - \sigma_m)/(\sigma_r - \sigma_m)$.

For unidirectional arrangement of short reinforcing fibers, in the case of retaining the identical bulk fraction of reinforcing fibers in the matrix, the same qualitative picture was established, as for long fibers. True, this is in case the length of the reinforcing fiber L is greater than the critical value L_c. In this

case, the tension load, which can be withstood by the combined
material, is distributed between the matrix and the reinforcing
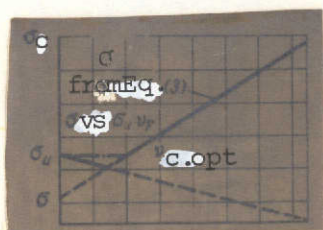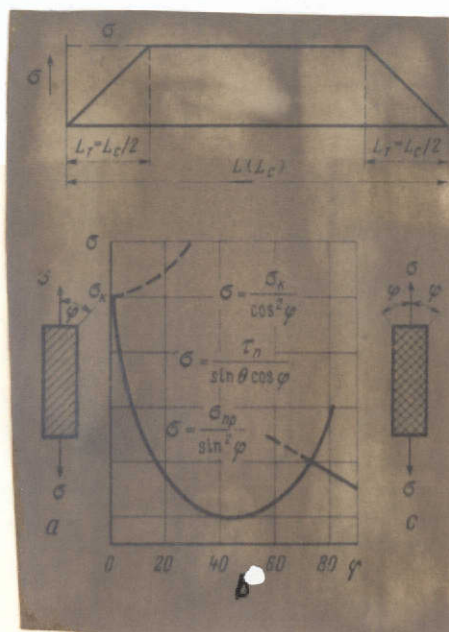fibers along the interface of the two phases.

Fig. 7. Theoretical change in
strength of combined material
σ_c vs. bulk fraction v_q, for
reinforced material with long
strengthening filaments.

This is connected with the
fact that mixing of the matrix
and reinforcing fibers is not
uniform. For the case of brit-
tle fibers incorporated into a
metallic matrix, when the matrix
flows plastically without harden-
ing, it can be considered that the
the entire matrix flows, due to
tangential shear stress τ_m. For
these conditions, the stress on
the reinforcing filaments in-
creases linearly from the ends
of the filaments, as is seen in
Fig. 8.

Fig. 8. Expected change in
stresses along filaments placed
in a metallic matrix (upper fig-
ure): a--stress applied at angle
to reinforcing filaments; b--
change in failure stress σ with
change in angle Φ, for combined
material shown in Fig. 8a; c--
crossed arrangement of reinforc-
ing fibers, for purpose of in-
creasing Φ_{crit}.

In order for the stresses generated to cause failure, the
transmitting length L_t must be

$$\sigma_r \pi d^2/4 = \tau_M \pi d L_t$$

where d is the filament diameter, i.e., $L_t = \sigma_r d/4\tau_m$.

Since transmission of the force takes place through both ends
of the filament, the minimum critical length of the filament L_c

can be determined from the expression

$$L_c = 2L_r = \sigma_r^{d}/\tau_u^2,$$
$$\text{or} \quad L_c/d = \sigma_r/2\tau_u. \tag{4}$$

Expression (3) can be used for reinforcing with short fibers, assuming that σ_r can be replaced by the mean stress $\bar{\sigma}$, which, at the ends of the fibers, will be

$$\bar{\sigma}L = \sigma_r(L - L_c) + (\sigma_r/2)L_c,$$
$$\bar{\sigma} = \sigma_r[1 - (L_c/2L)].$$

Since the described method has been used for estimating the critical length L_c, in which the number of filaments failing n_r and elongated n_{pr} was allowed for in the failed section of the combined material, L_c then is calculated by the formula

$$L/L_c = (n_r/n_{pr}) + 1.$$

If the directions of the applied stress and the reinforcing do not coincide, as is evident in Fig. 8a, failure can take place in one of the following ways.

1. Plastic flow of the matrix takes place in a direction /177 parallel to the reinforcing filaments. The stress leading to failure σ can be determined from the expression $\sigma = \sigma_c/\cos^2 \phi$, shere $\sigma_c = \sigma_b$ of the combined material.

2. Destruction of the matrix by shear in planes parallel to the matrix; then, σ failure can be determined from the expression $\sigma = \tau_u/\sin \phi \cos \phi$, where τ_u is the tangential stress in the matrix.

3. Destruction of the matrix by flow transverse to the direction of the reinforcing filaments. In this case, σ can be determined from the expression $\sigma = \sigma_{up}/\sin^2 \phi$, where σ_{up} is the strength of the matrix.

These failure criteria, connected with change in failure stress σ_u and with change in ϕ, are seen in Fig. 8b.

Thus, the value of ϕ_{cr} is limited to an angle of several degrees. If ϕ is greater than ϕ_{cr}, the strength of the calibrated material drops sharply.

However, the value of ϕ_{cr} can increase significantly, by means of a crossed arrangement of the reinforcing fibers (see Fig. 8c). In the case of a viscous matrix, plastic flow decreases the concentration of stresses around the ends of the reinforcing filaments. The viscosity of the combined material can also increase, by means of weakening the force of adhesion at the matrix-reinforcing filament boundary. Cracks, usually propagating perpendicular to the contact face of the two phases, will deviate along the boundary in this case, causing separation of the filaments and matrix.

The criteria of reinforcing and failure, as well as the strength properties of combined materials, produced by means of reinforcing a metallic matrix with unidirectional fibers, has been discussed.

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